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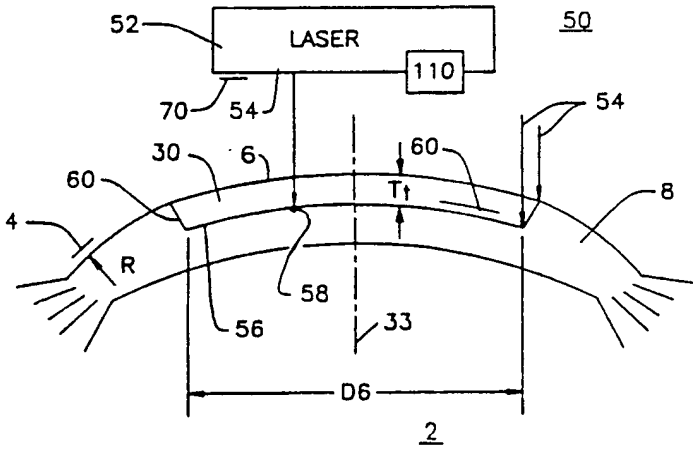

(57) Abstract

Low energy, ultra-short (femptoseconds) pulsed laser radiation is applied to the patient's eye (2) in one of a number of patterns such that the exposed ocular tissue is ablated (56) or excised (54) through the process of optical breakdown or photodisruption in a very controlled fashion. The process can be gentle enough that the invention makes possible the performance of a number of surgical procedures that in the past could not have been performed at all, such as capsulorhexis, or were performed in a fashion that provided less than an ideal result or excessive trauma to the ocular tissue. Such latter applications include the making of incisions for corneal transplantation, radial and arcuate keratotomy, and intra-stromal cavitation. Using the laser inside the eye allows the surgeon to perform glaucoma operations such as trabeculoplasty and iridotomy, cataract techniques such as capsulectomy, capsulorhexis and phacoablation, and vitreoretinal surgery, such as membrane resection. The various procedures are accomplished by controlling energy flux or irradiance, geometric deposition of beam exposure and exposure time.

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METHOD OF PERFORMING OPHTHALMIC SURGERY

This application describes various surgical procedures employing a femptosecond laser described in a co-pending application of Shui T. Lai.

FIELD OF INVENTION

The invention relates broadly to surgical procedures of the eye. Such procedures include operations on the outer covering of the eye, or cornea, the iris and trabecular meshwork, the lens, and the vitreous and retina.

BACKGROUND OF THE INVENTION

In many cases, the procedures proposed have been performed in the past, but they have been accompanied by inaccuracy, trauma or ocular damage. In others, they have never been capable of performance because of surgical or technical considerations.

United States patent 4,309,998, Aron nee Rosa et. al., issued January 12, 1982, described the process of optical breakdown and photodisruption, whereby tissues, transparent or not,to a given wavelength of laser radiation can be excised or ablated by sharply focusing the beam at a specific point in the tissue while achieving a local power density at the site above the threshold (greater than 10 12 Watts/cm2) for optical breakdown,

a complex process involving ionization, plasma formation, and mechanical disruption by secondarily propagated waves. In this patent, the inventors used a YAG laser, emitting at 1064 nm, with pulse widths in the range of 20-400 ps and energies in the range of 2-5 mj to ablate opacities from the lens of the eye, open posterior lens capsules, and cut vitreous membranes.

In their publication, "Ophthalmic Neodymium Yag Lasers", Keates et. al. describe the basic principles underlying photodisruption with lasers. The definition of power density is given as the ratio of beam energy in Joules divided by pulse length in seconds times focal spot area in square centimeters. Thus the shorter the pulse length or the smaller the spot, the greater the power density, which is the determinant in achieving optical breakdown, whose threshold is given as 10^{12} W/cm^2. Also, it is described that high pulse power and low energy pulses are preferred for cutting or perforating tissue, and that low pulse power and high energy pulses is associated with thermal and biophysical damage mechanisms. By using shorter pulses, an appropriate power density can be achieved in any tissue with a lower energy level, which reduces shock waves and adjacent tissue damage.

United States patent 4,907,586, Bille and Brown, issued March 13, 1990, describes the use of the photodisruptive process for corneal and other eye surgery. In this patent, a quasi-continuous picosecond pulse width laser is used to create

optical breakdown in various tissues. The inventors describe, in general, the types of procedures that may be attempted with such a laser.

One of us (Shui T. Lai) has described technology for producing laser pulses in the femptosecond range, which, as based on the above discussion, allows high power densities to be achieved at much lower energy levels than any described in the art. Experimentally, we ablated tissue by photodisruption at various pulse widths and energy levels and have demonstrated the attainment of superior results with respect to the procedures described herein when operating in the femptosecond range as opposed to the picosecond range, with respect to pulse width. Light and electron microscopy have clearly demonstrated less adjacent damage, sharper incisions, and the ability to more accurately localize the surgical interaction, which is mandatory for optical success.

Corneal operations are typically performed for either therapeutic or optical considerations. In the therapeutic class are such procedures as lamellar keratoplasty and penetrating keratoplasty or corneal transplantation. The classic operation of lamellar keratoplasty is designed to remove scarred, irregular or opaque corneal tissue from across the visually critical central optic zone of the cornea and replacement with a partial donor cornea to restore the corneal shape and clarity, thereby improving vision. It relates also